

Modeling Lean Premixed Combustion in Gas Turbines

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Abstract

A new model has been developed for simulating steady-state, turbulent, gaseous combustion in practical, three-dimensional devices. Although the model was specifically developed for lean, premixed combustion of natural gas in gas turbines, it has general applicability to a variety of gaseous combustion problems and configurations. The model uses a hybrid Eulerian/Lagrangian approach with the Monte Carlo velocity-scalar pdf method coupled to an unstructured-grid flow solver. It was developed from the foundation of PCGC-3, a three-dimensional gas and particle combustion code (Hill and Smoot, 1993), and PDF2DS, a two-dimensional velocity-scalar pdf code (Correa and Pope, 1992). The flow solver calculates the flowfield for an assumed density field and the Monte Carlo pdf solver solves the transport equation for the joint pdf of velocity and scalars.

The unstructured-grid flow solver uses primitive variables (u , v , w , p). It solves the incompressible, Navier-Stokes equations using a co-located, equal-order, control volume-based, finite-element method (Prakash and Patankar, 1985). The mass-weighted, skewed, upwind scheme of Schneider and Raw (1986) is used for the advection terms, while linear interpolation functions are used for the diffusion, pressure gradient and source terms. Rotational periodic boundary conditions are included. The discretized algebraic equations are solved using an iterative, tri-diagonal matrix algorithm. Turbulence is modeled using the k -model. Convective and radiative heat losses are modeled using a wall function method and a discrete ordinates radiation model (Jamaluddin and Smith, 1988), respectively. Turbulence/chemistry interactions are modeled using the velocity-composition, Monte-Carlo pdf approach (Pope, 1985). The pdf calculation includes a new chemical mechanism that was developed specifically for the conditions of lean premixed combustion of natural gas in land-based turbines (Mallampalli, et al., 1996).

In support of the modeling effort, an experimental program has been conducted to collect *in situ* data in a swirling, turbulent, premixed natural gas flame in an atmospheric pressure, laboratory-scale gas turbine combustor (LSGTC). These measurements have included multiple, instantaneous, CARS measurements of gas temperature and major species concentrations (CO , CO_2 , O_2 , and N_2); multiple instantaneous LDA measurements of axial, tangential, and radial velocity; and multiple instantaneous PLIF images of selected combustion intermediates (OH , and CH). Results are in the form of mean and standard deviation iso-contour maps of gas temperature, selected species concentration, and mean and instantaneous PLIF images of OH and CH . These data are being collected at medium and high swirl numbers ($\text{SN} = 0.74$ and 1.29) and at fuel equivalence ratios of 0.65 and 0.80 . The poster paper presents example results for the fuel-lean case ($\phi = 0.65$) at the high swirl number ($\text{SN} = 1.29$).

The velocity-composition pdf model, coupled with a mean flow CFD model, was used to describe the turbulent fluid flow, heat transfer, chemistry, and their interactions in the swirling, lean premixed, methane-

air combustor described above. A premixed natural gas flame was stabilized in the axi-symmetric, laboratory-scale, gas-turbine combustor (LSGTC). A reduced, 5-step chemical mechanism, for describing fuel oxidation and NO chemistry, was used in this LSGTC model. NO emissions from thermal, N_2O -intermediate, and prompt pathways were described in this 5-step mechanism. The chemistry calculations were performed efficiently with an *in-situ* look-up table. An axi-symmetric, unstructured grid, consisting of 2283 vertices and 4302 triangular elements, was used for solving the Eulerian, mean flow equations and the vertices were used to store mean statistics for solving the Lagrangian, fluid particle (310,000 fluid particles) equations. Predicted velocity and composition statistics were compared to measurements in the LSGTC for lean equivalence ratios of 0.8 and 0.65. The comparisons of predicted mean velocity and temperature were reasonably good throughout the combustor. The location and magnitude of peak axial velocity was well represented by the model at near inlet regions, though the negative mean axial velocity in the internal recirculation zone was over-predicted. The predicted maximum mean temperature and the penetration zone of the cold, unburned fluid were in reasonable agreement with the experimental data. Correct trends in CO and NO with equivalence ratio were predicted with the model. The *in situ* tabulation method was used to represent the chemical kinetics in this axi-symmetric combustor without requiring significant CPU time and memory.

The model has also been evaluated with premixed combustion data from laboratory flames stabilized by swirl, bluff-body, and a pilot flame (Cannon et al., 1997), and it has been applied to several practical, industrial, gas turbine premixers and combustors (Meng et al., 1997).

References

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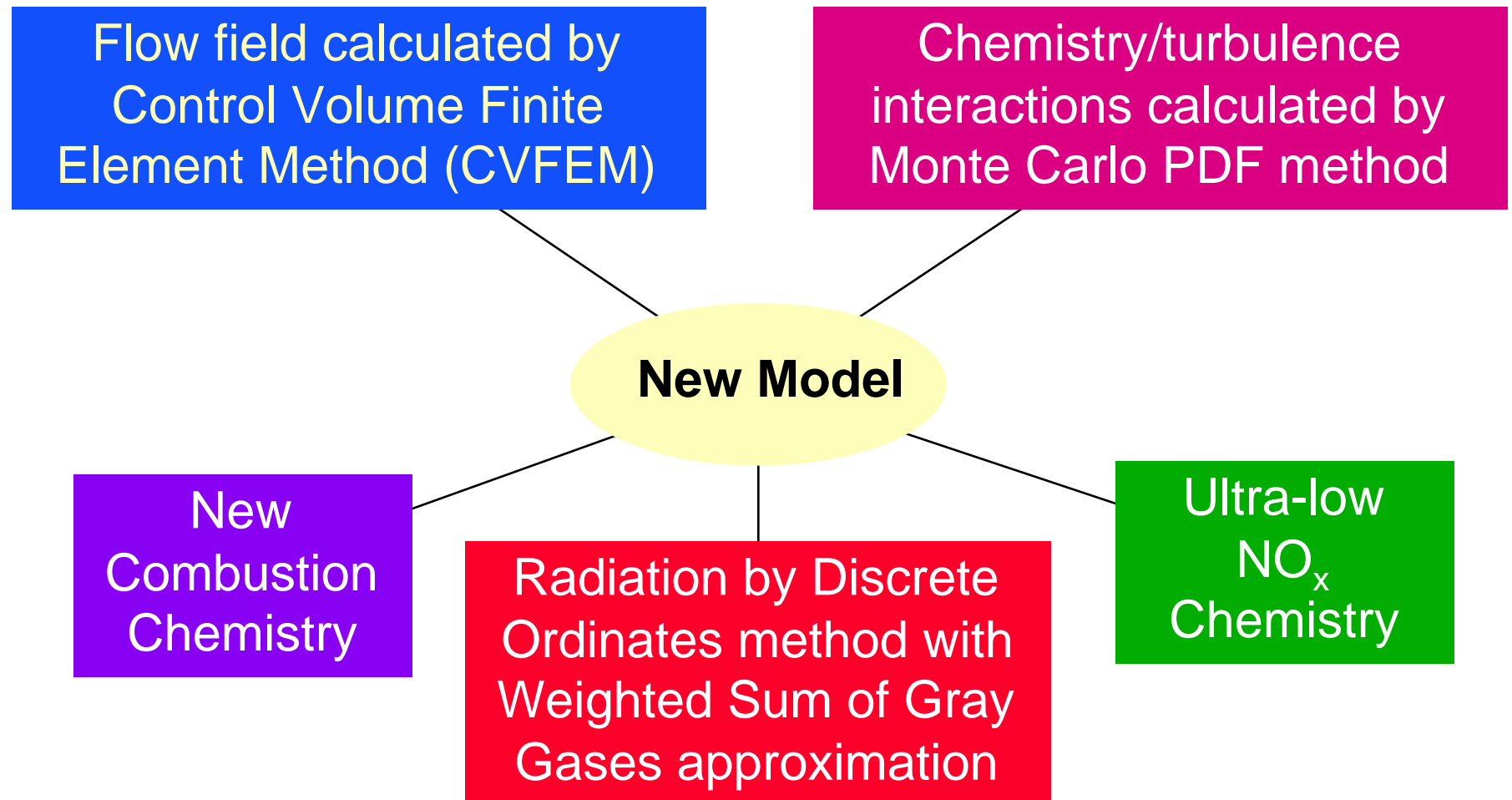
**Start Date: 1 September 1993
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DOE Contract No. DE-FC21-92MC29061

Objectives

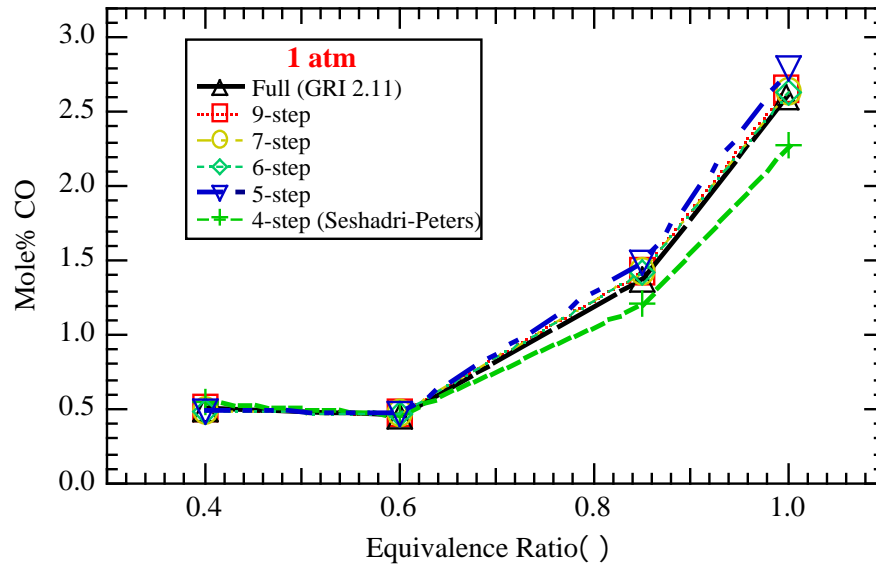
- **Develop an improved model for advanced gas turbine systems**
 - 3-dimensional
 - Curved boundaries
 - Submodel development for lean premixed systems
- **Obtain data for model evaluation**
- **Evaluate the model**
- **Apply the model to practical systems**
- **Provide training and distribute the code**

Critical Elements of the New Model

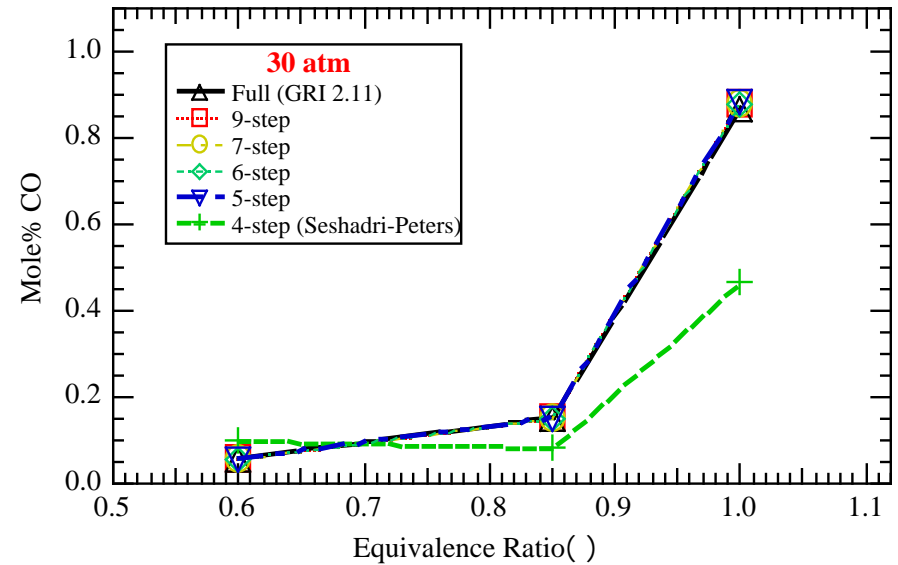


PSR Predictions of CO at 1 and 30 atm

$T_{\text{inlet}} = 600 \text{ K}$, and $\tau = 2 \text{ ms}$



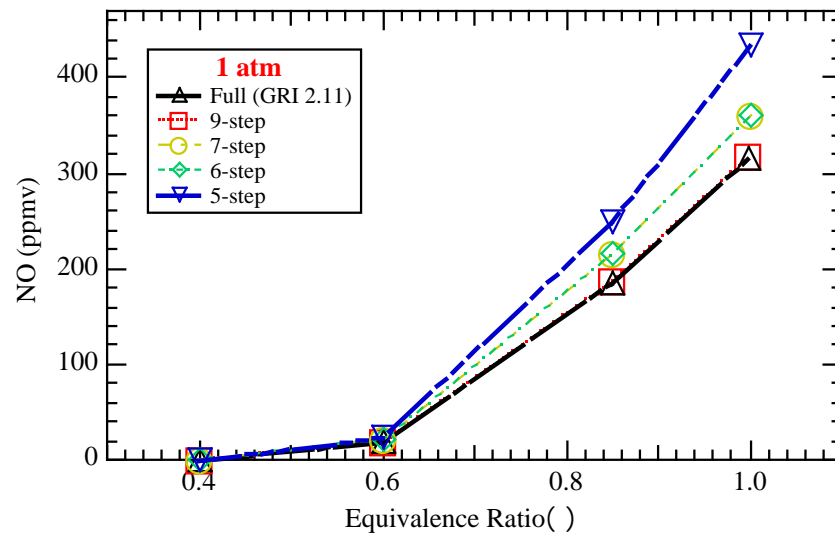
(a) 1 atm



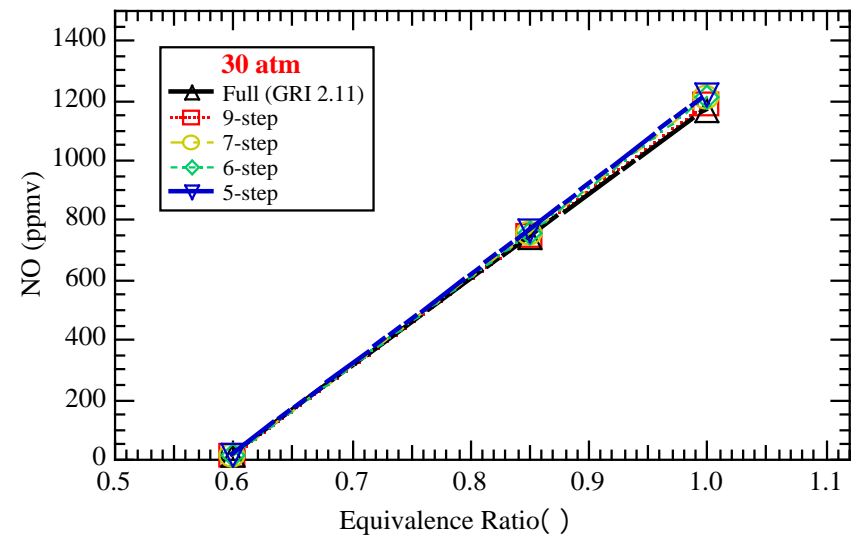
(b) 30 atm

PSR Predictions of NO at 1 and 30 atm

$T_{\text{inlet}} = 600 \text{ K}$, and $\tau = 2 \text{ ms}$



(a) 1 atm



(b) 30 atm

5-Step Chemistry

Mallampalli et al., 1996



I



II



III



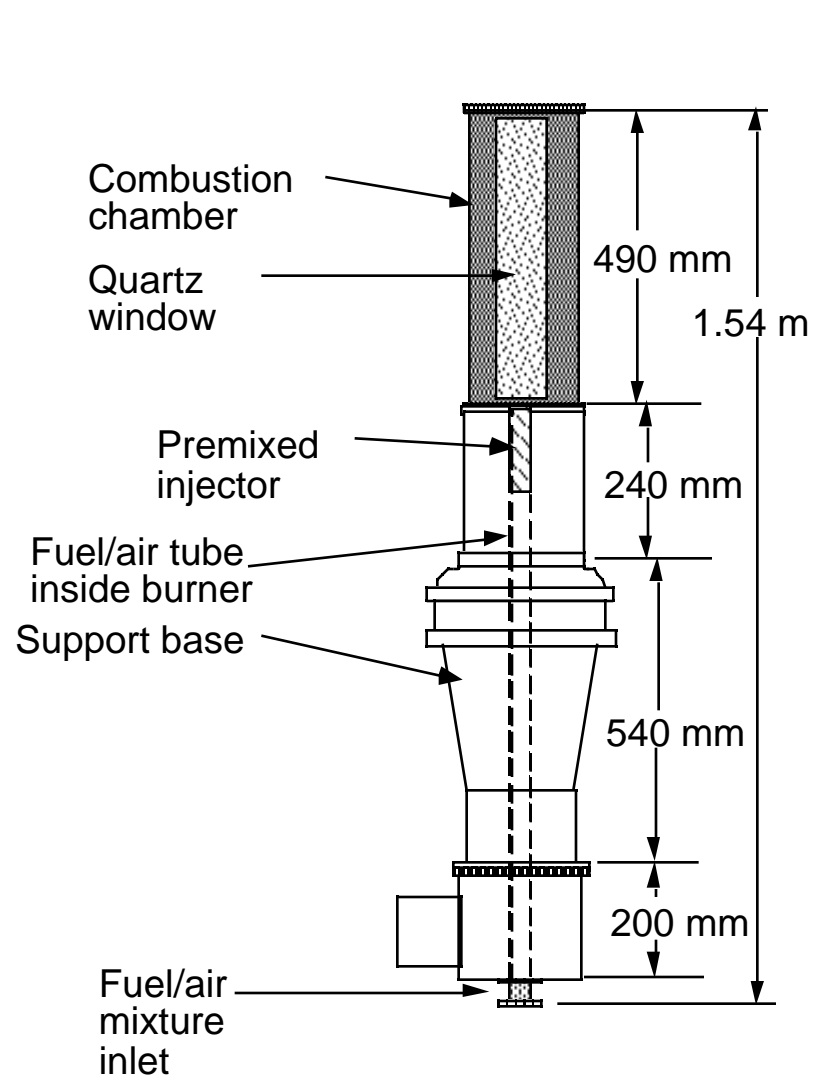
IV



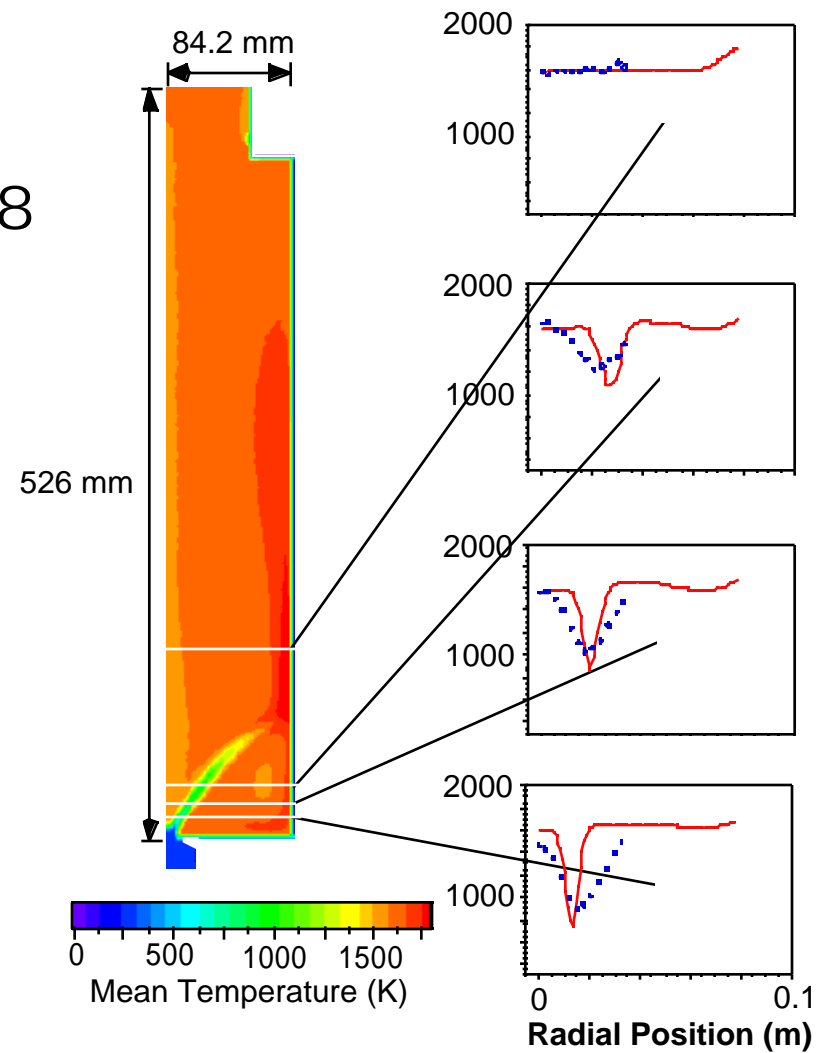
V

BYU Combustor

Swirl-stabilized

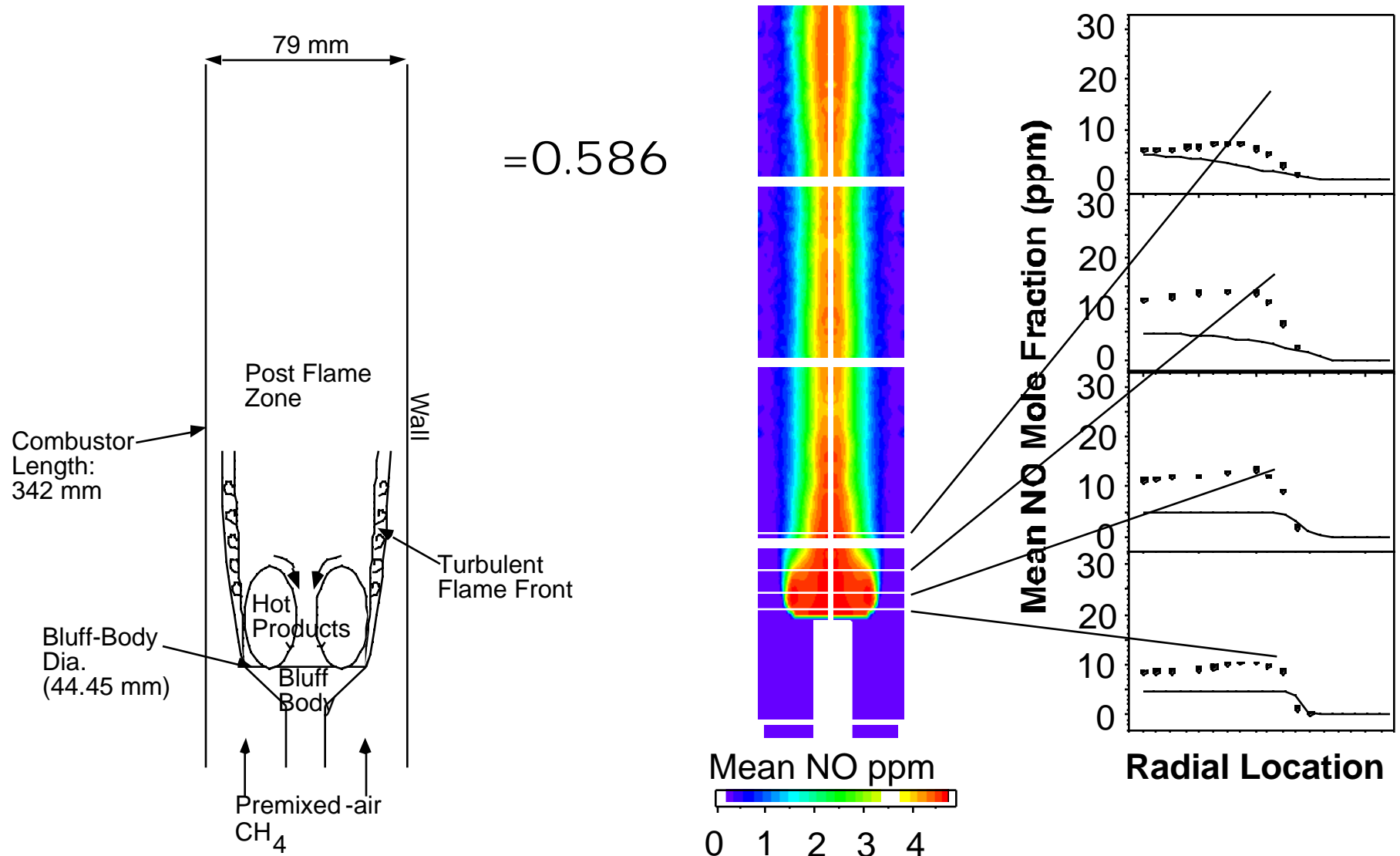


=0.8



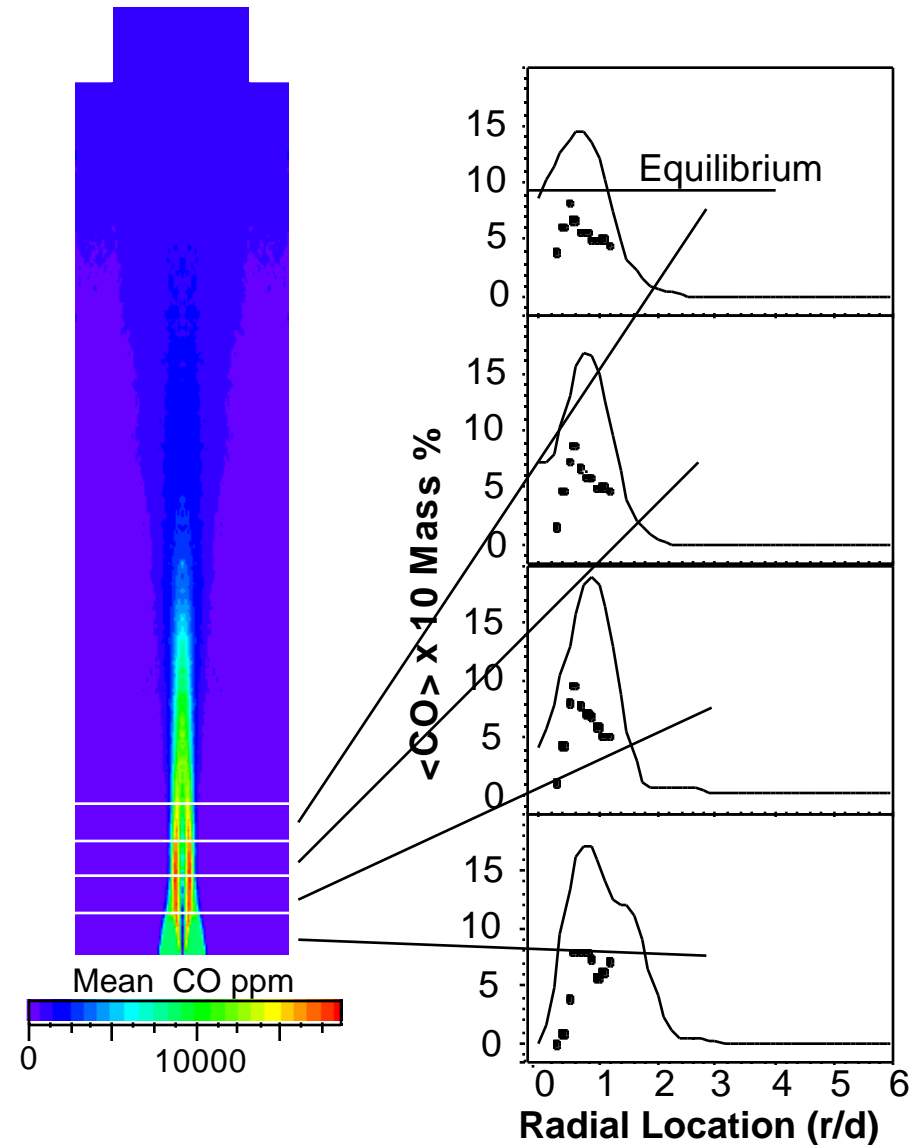
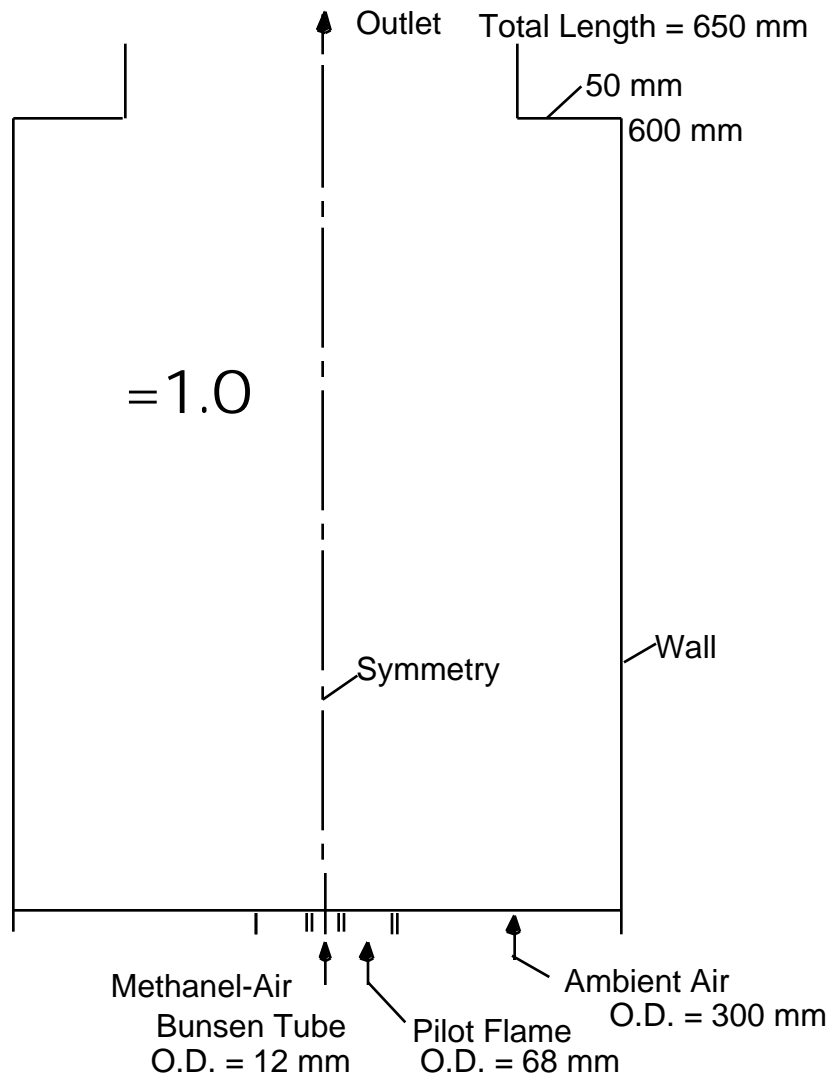
Vanderbilt Combustor

Bluff-body stabilized (Nandula et al., 1996)



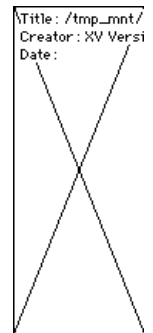
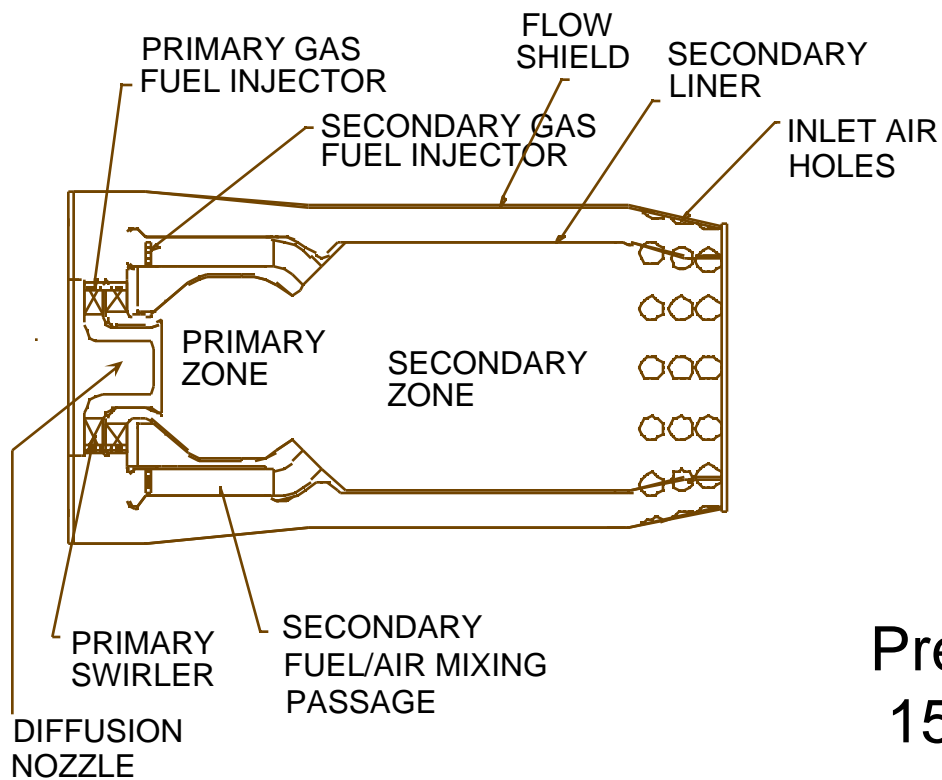
Piloted Bunsen Burner

(Chen et al., 1996)



Westinghouse Combustor

(Sharifi et al., 1995)

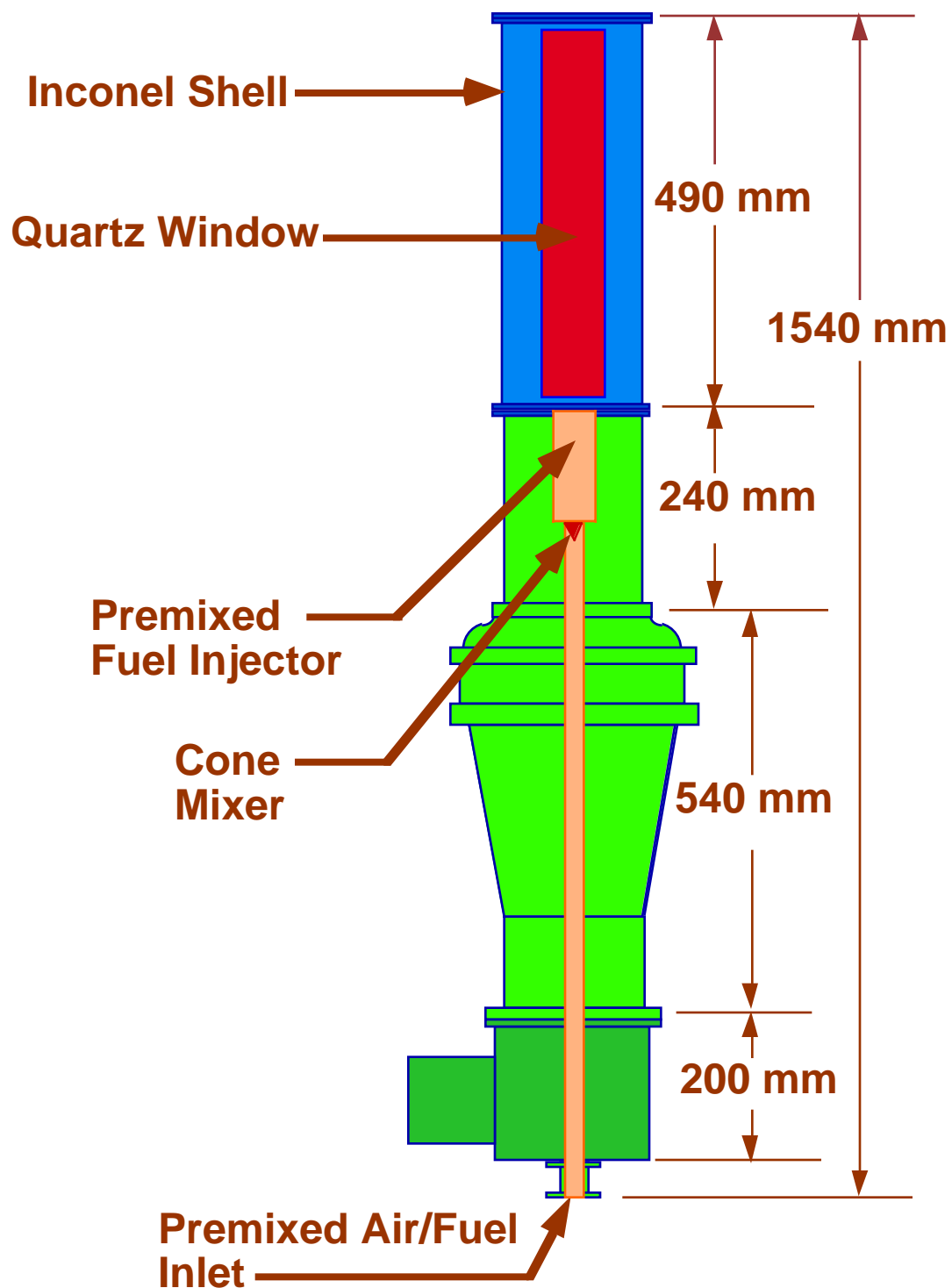


Predicted NO_x ppm (adjusted to 15% O_2) in primary zone

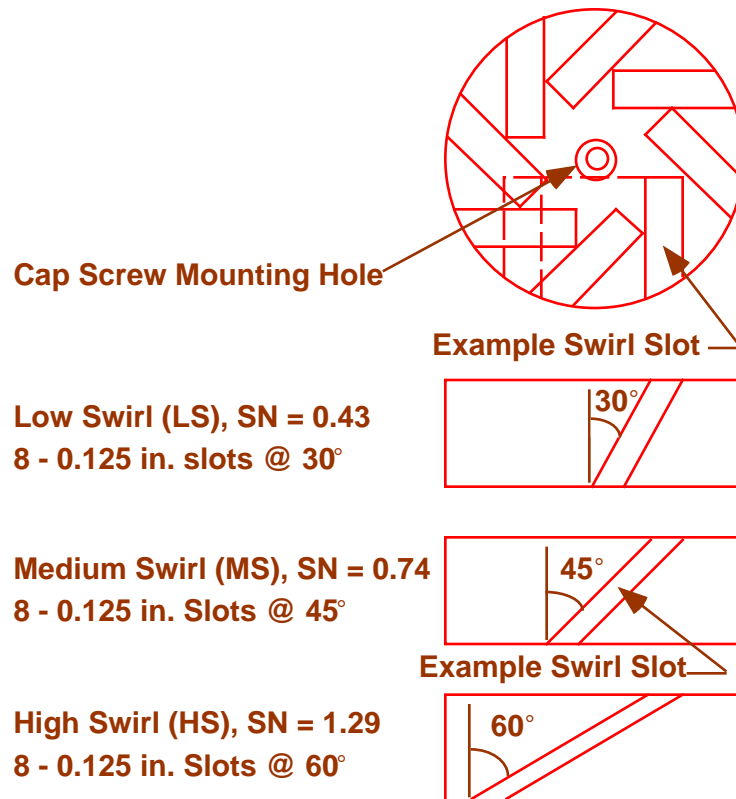
BYU Experimental Capability

- Laboratory-scale, atmospheric pressure, model gas-turbine combustor (LSGTC) with good optical access
- Premixed and non-premixed fuel injectors
- Gaseous (nat'l gas and propane) and liquid (ethanol) fuels
- Optical instruments => instantaneous and non-intrusive
 - *Film and video cameras => overall flame structure*
 - *CARS => T , CO , CO_2 , O_2 and N_2 directly
 H_2O , and H^* and C^* by elemental balance*
 - *LDA => Axial, tangential or axial, radial velocities*
 - *PLIF => OH , CH , NO two-dimensional images*

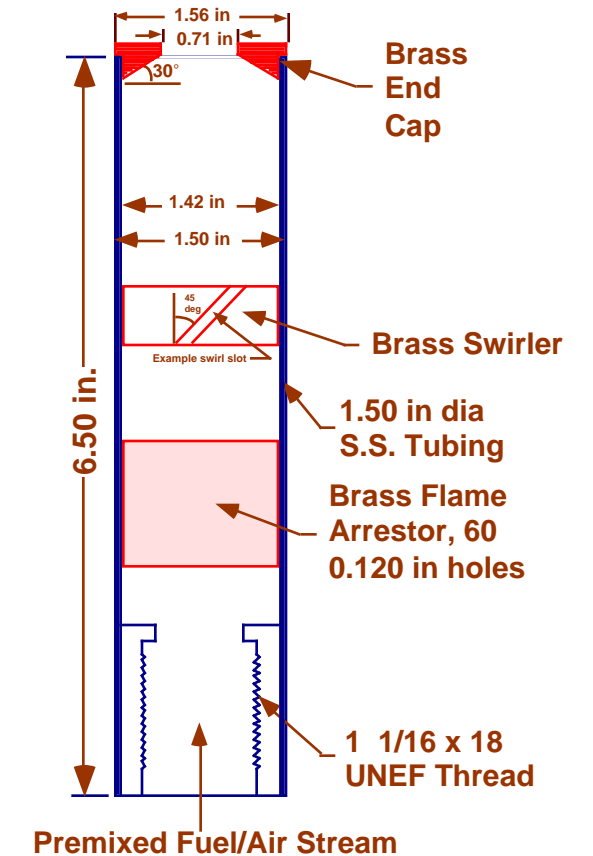
Atmospheric Laboratory-Scale Gas Turbine Combustor (LSGTC)



ATS Swirling, Turbulent, Premixed Fuel Injector



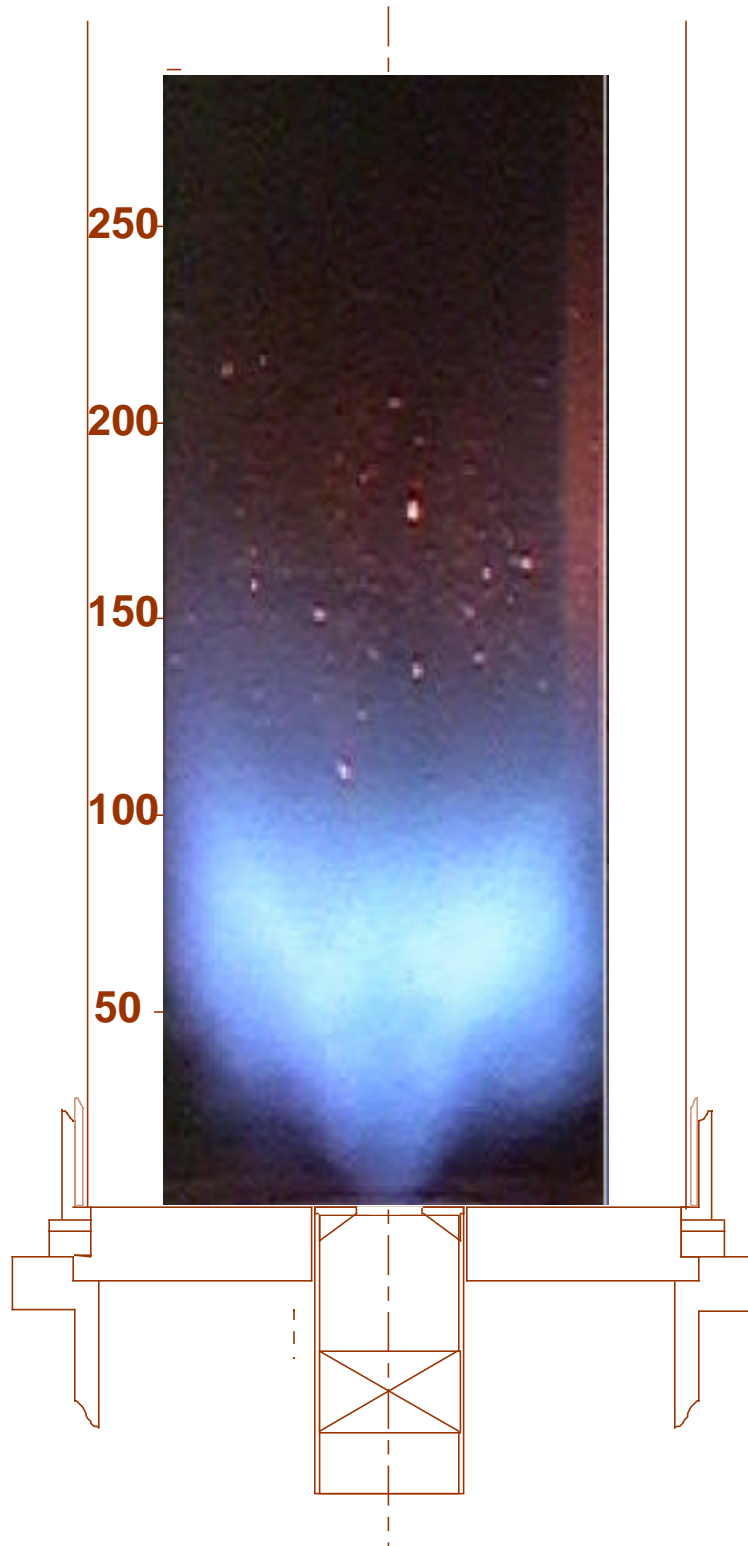
A) Details of Brass Swirlers



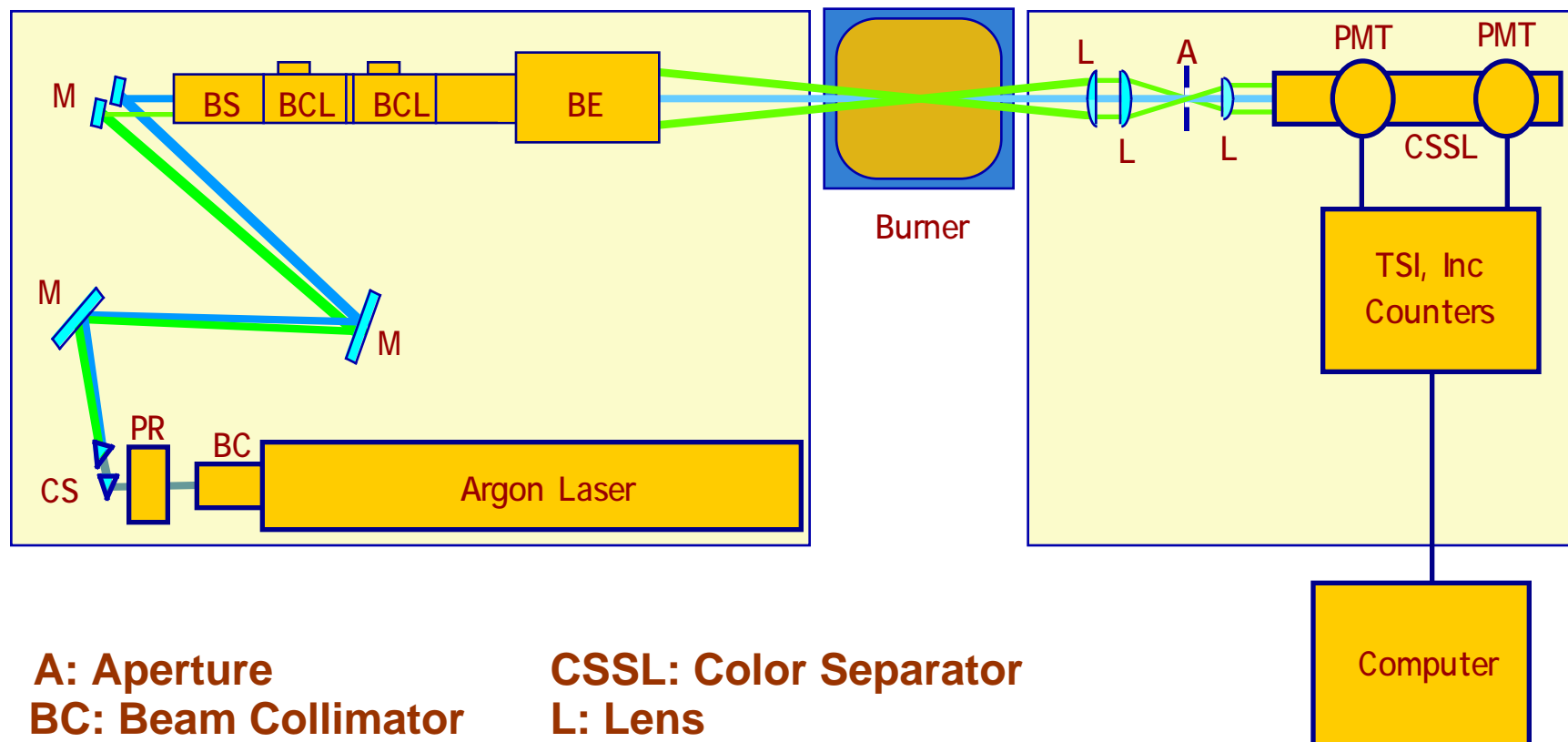
B) ATS Premixed Burner Tube

Video Image of Premixed Natural Gas/Air Flame

(ATS-MS Burner, 500 slpm Air Flow Rate, $\phi = 1.0$)



Schematic of LDA Installation on the LSGTC



A: Aperture

BC: Beam Collimator

BCL: Bragg Cell

BE: Beam Expander

BS: Beam Separator

CS: Color Separator

CSSL: Color Separator

L: Lens

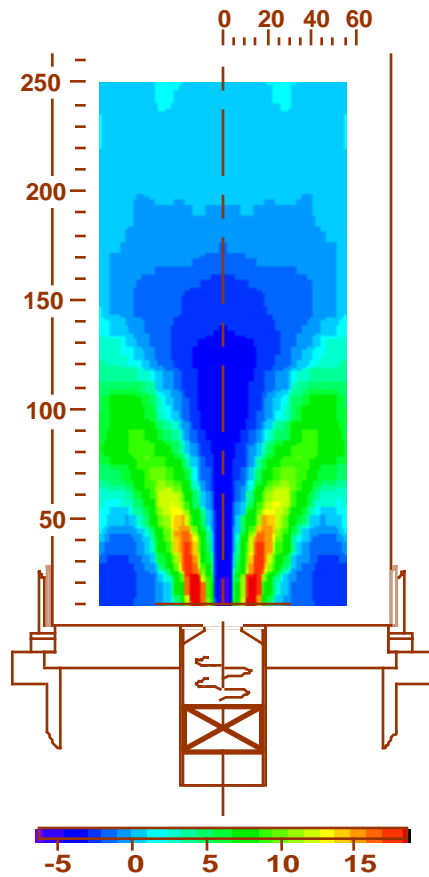
M: Mirror

PMT: Photomultiplier Tube

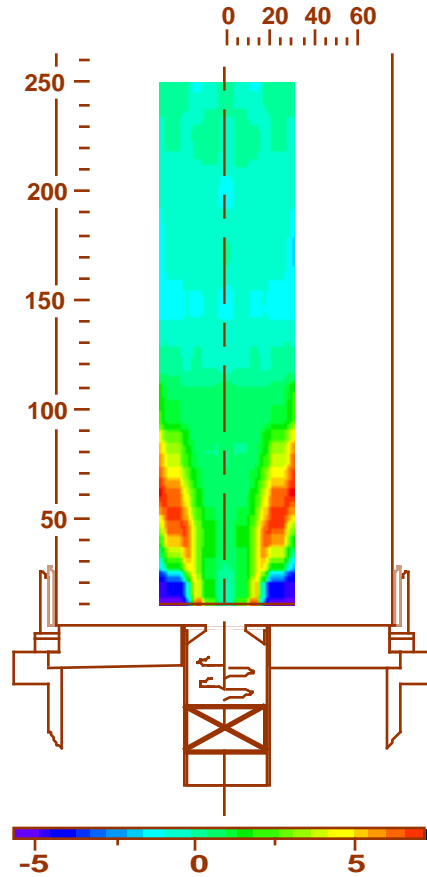
PR: Polarization Rotator

Iso-Velocity Contours in the LSGTC with the ATS-MS Burner

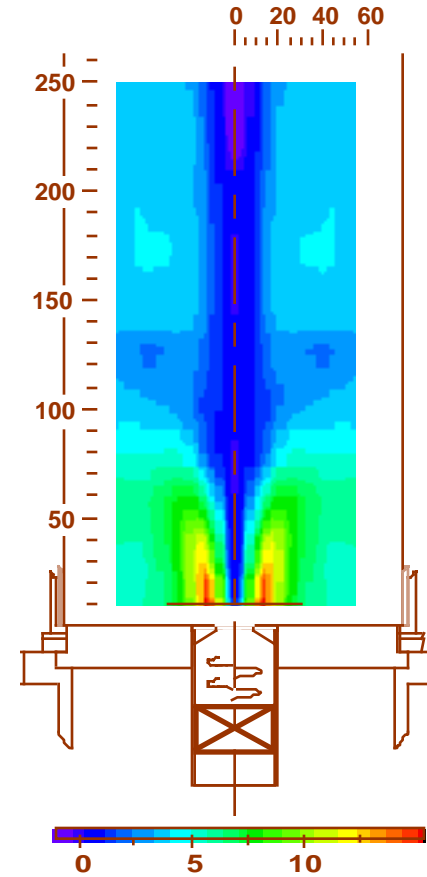
(Premixed Natural Gas/Air, Air Flow Rate = 500 slpm, $\phi = 0.65$)



A) Mean Axial Velocity, m/s

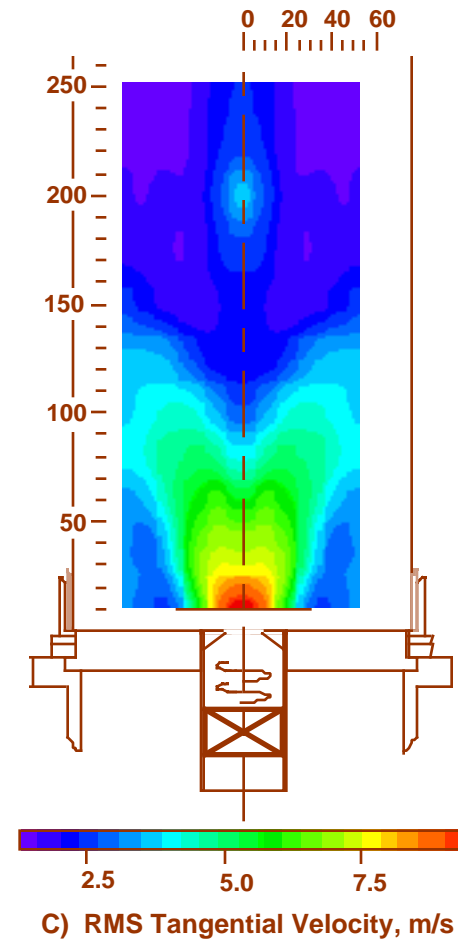
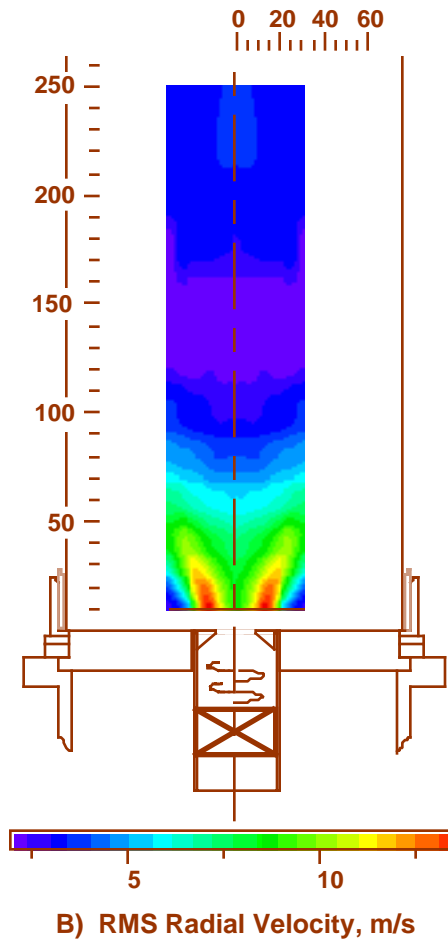
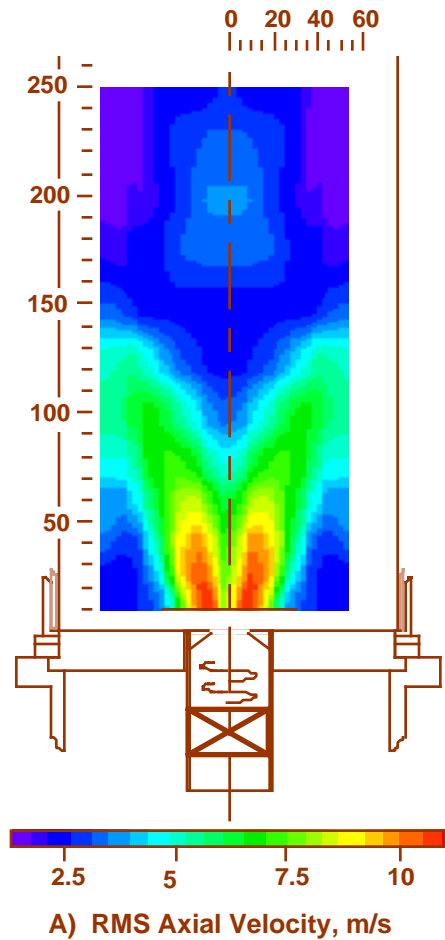


B) Mean Radial Velocity, m/s



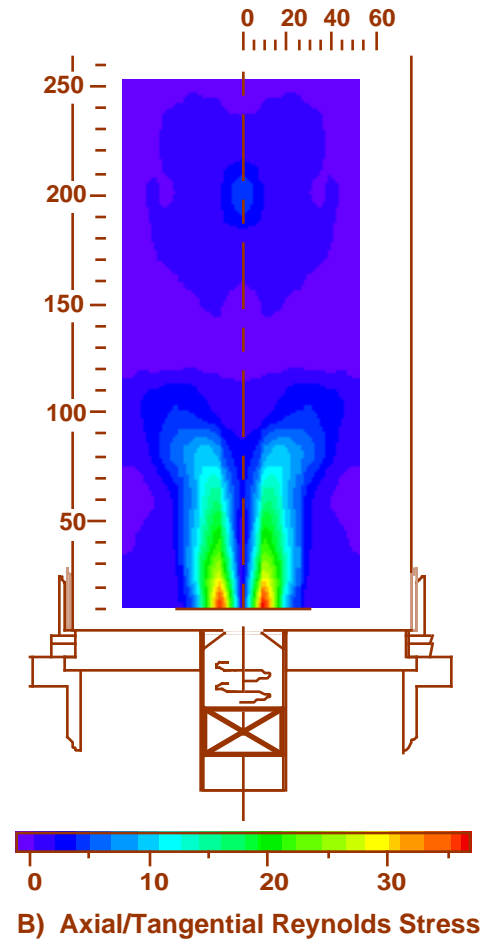
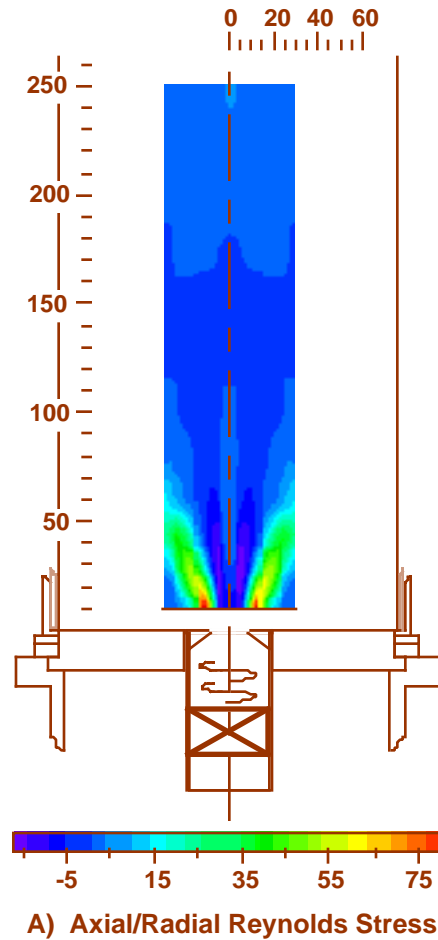
C) Mean Tangential Velocity, m/s

RMS Velocity Contours in the LSGTC with the ATS-MS Burner (Premixed Natural Gas/Air, Air Flow Rate = 500 slpm, $\phi = 0.65$)

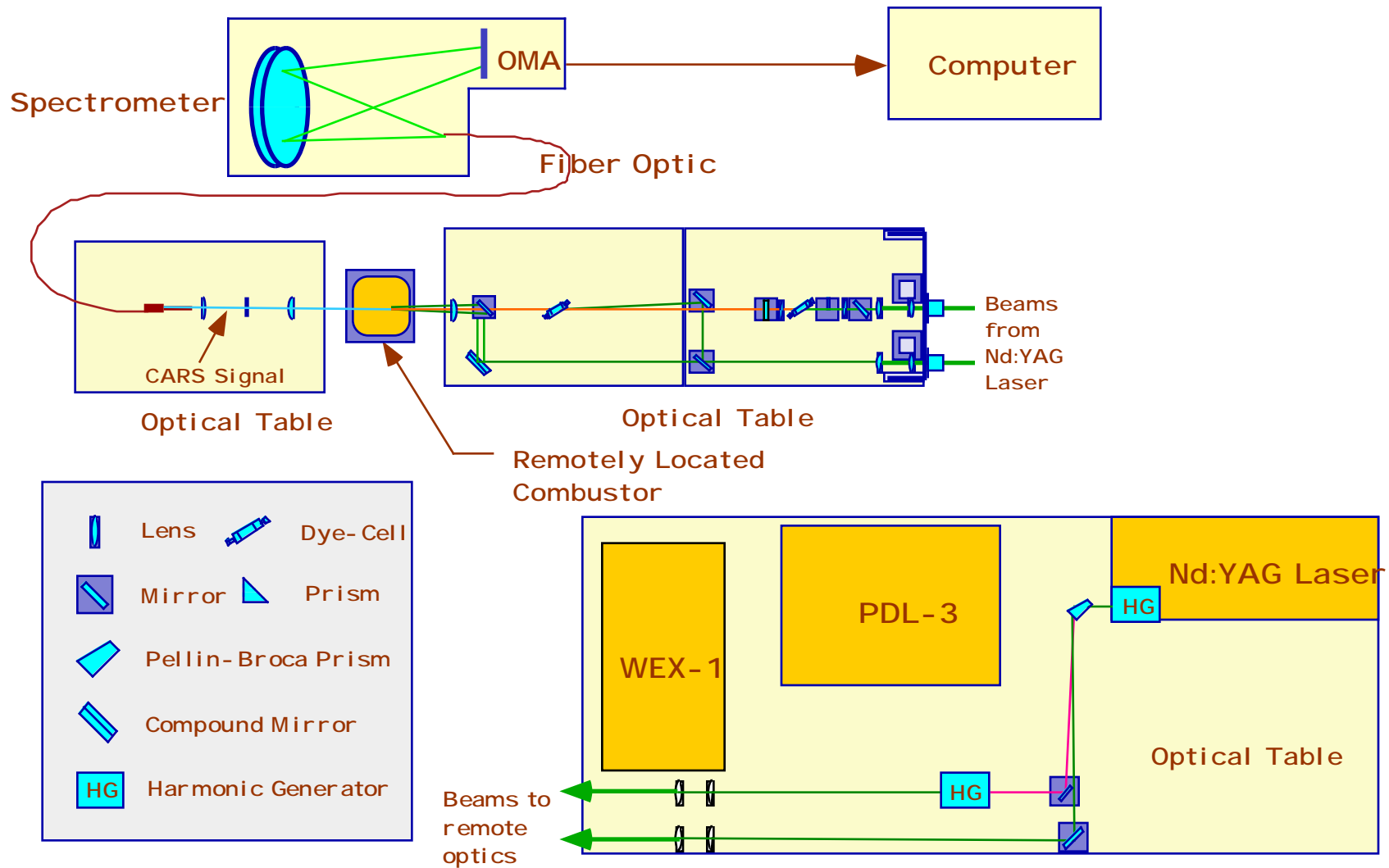


Reynolds Stress Contours in the LSGTC with the ATS-MS Burner

(Premixed Natural Gas/Air, Air Flow Rate = 500 slpm, $\phi = 0.65$)

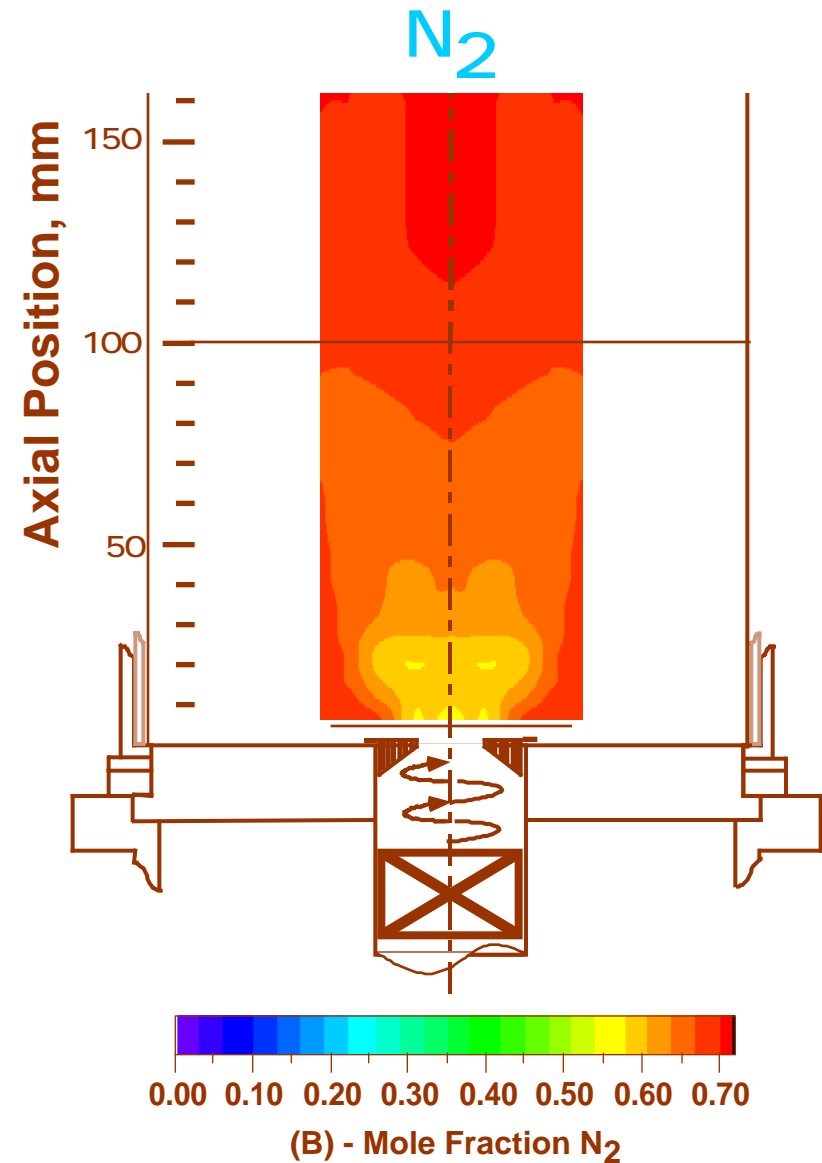
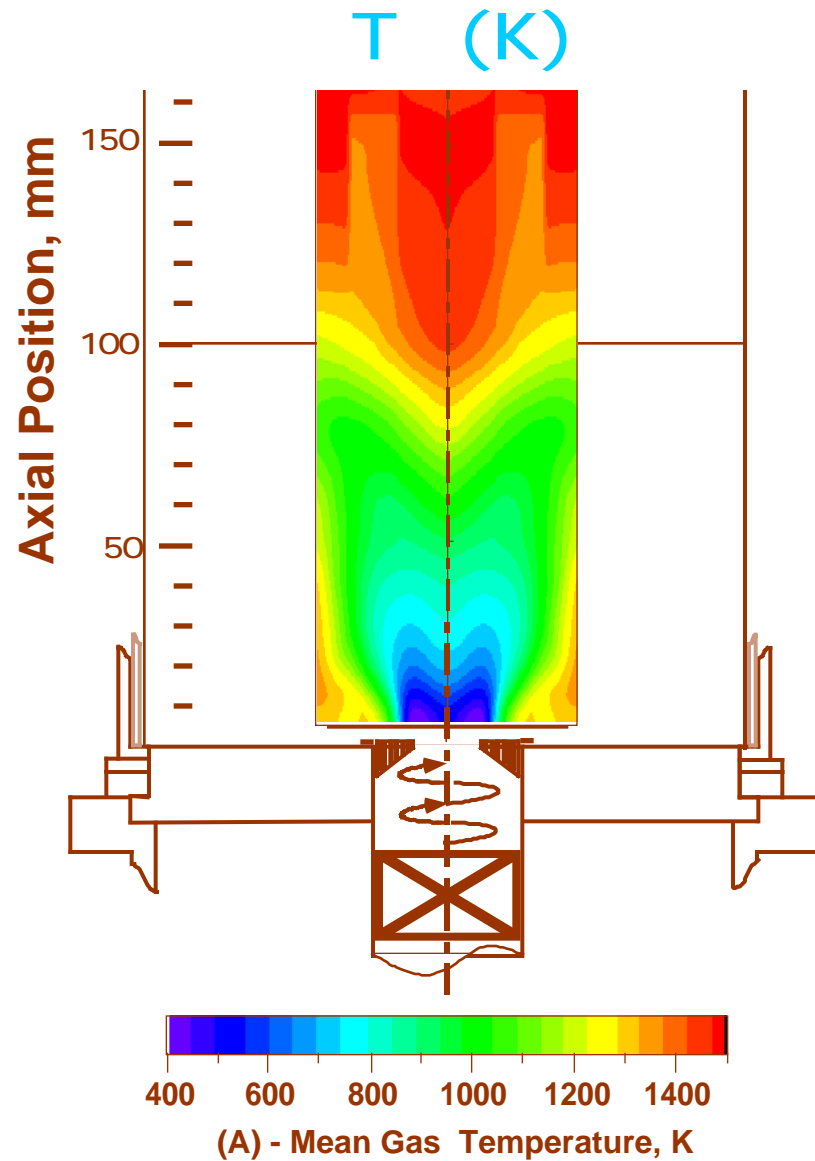


Schematic of Dual Dye, Single Stokes CARS Installation on the Laboratory-Scale Gas Turbine Combustor (LSGTC)



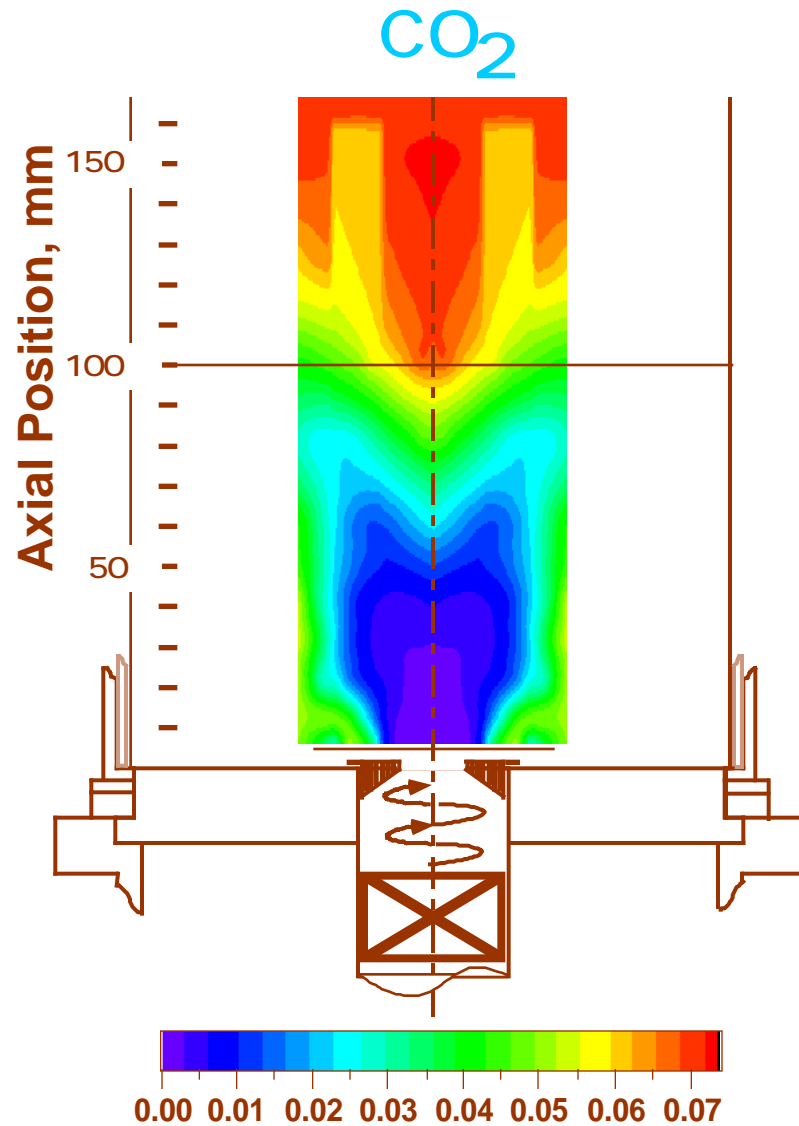
Iso-Temperature and Iso-N₂ Concentration Contours with the ATS-MS Burner

(Premixed Natural Gas/Air, Air Flow Rate = 500 slpm, $\phi = 0.65$)

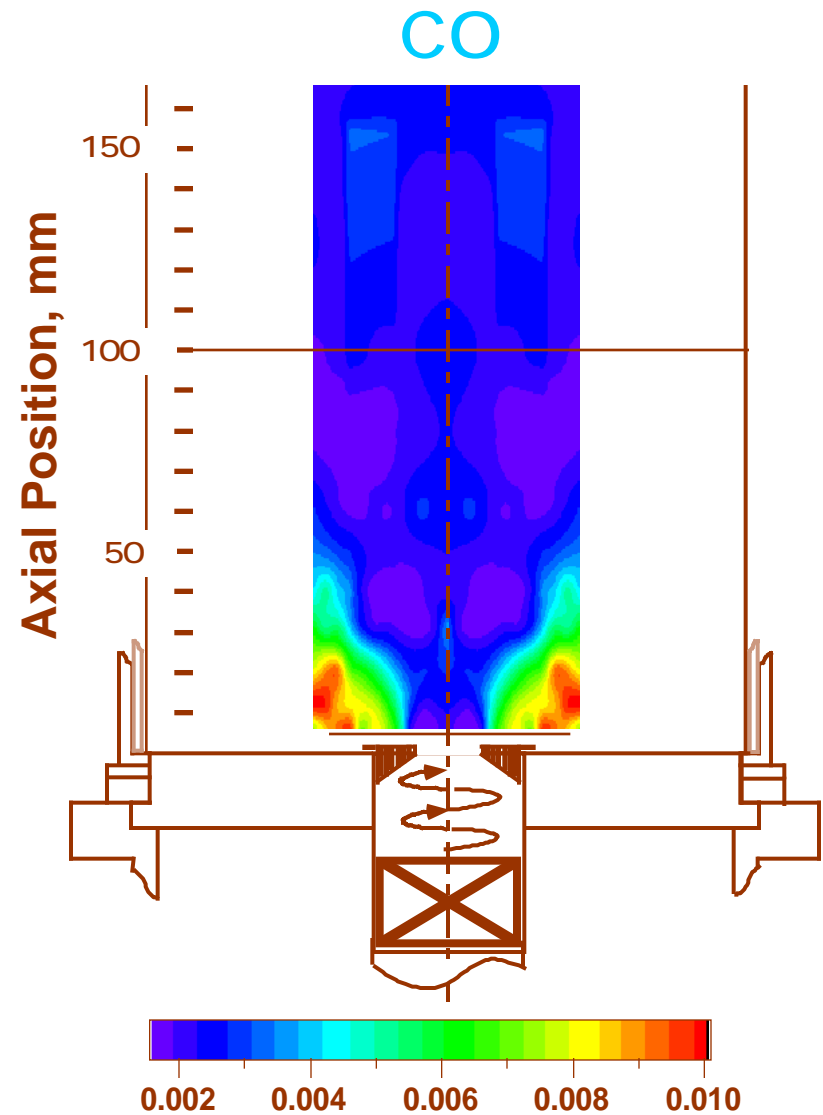


Iso- CO_2 and Iso-CO Concentration Contours with the ATS-MS Burner

(Premixed Natural Gas/Air, Air Flow Rate = 500 slpm, $\phi = 0.65$)



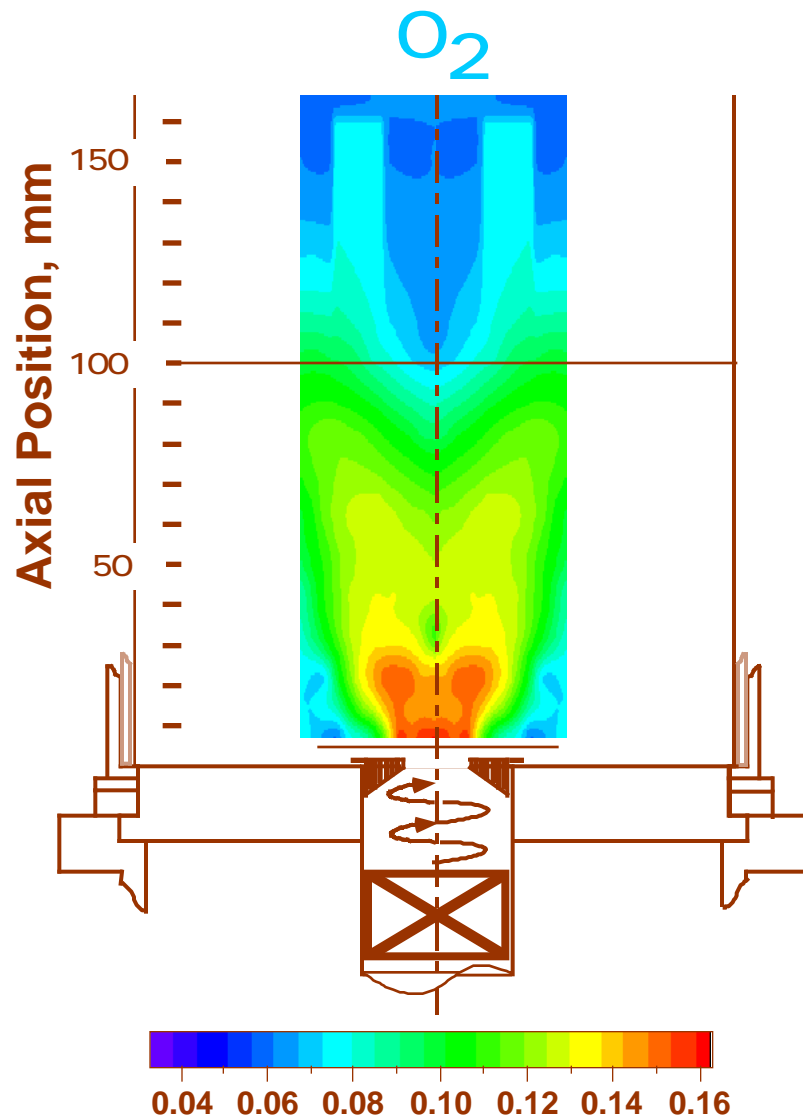
(C) - Mole Fraction CO_2



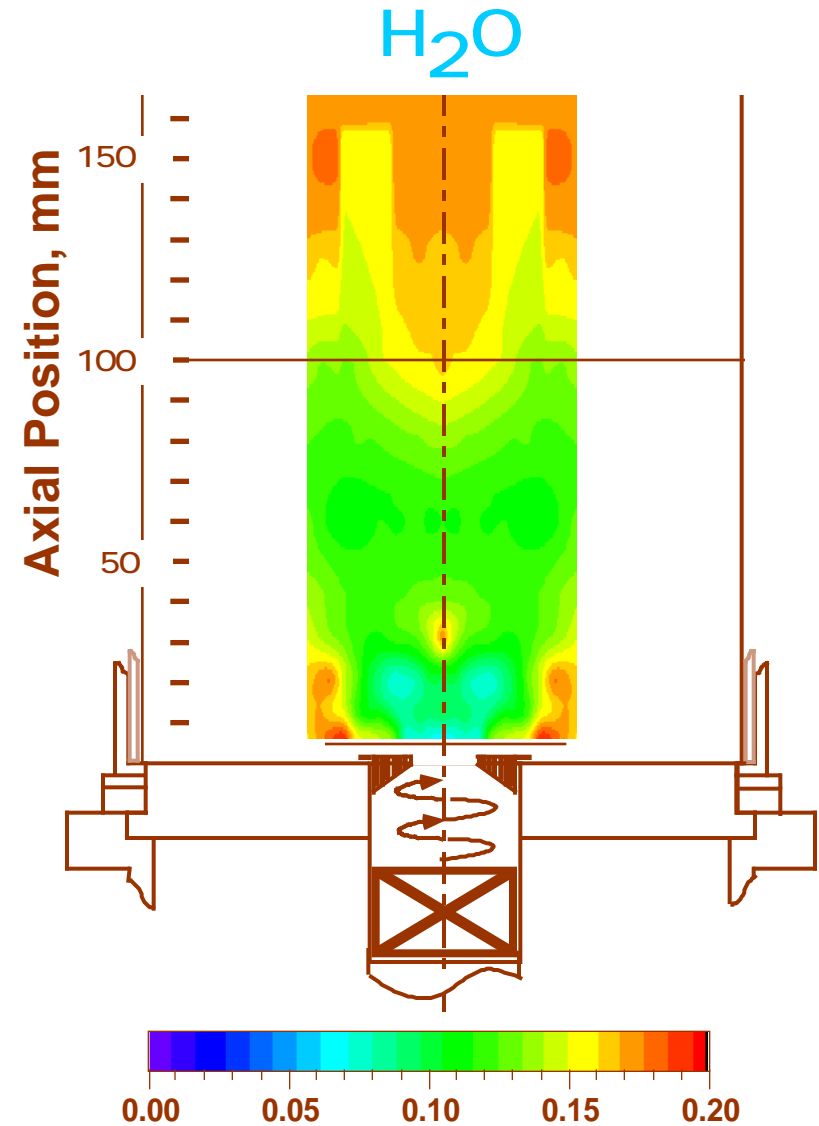
(D) - Mole Fraction CO

Iso-O₂ and Iso-H₂O Concentration Contours with the ATS-MS Burner

(Premixed Natural Gas/Air, Air Flow Rate = 500 slpm, $\phi = 0.65$)



(E) - Mole Fraction O₂

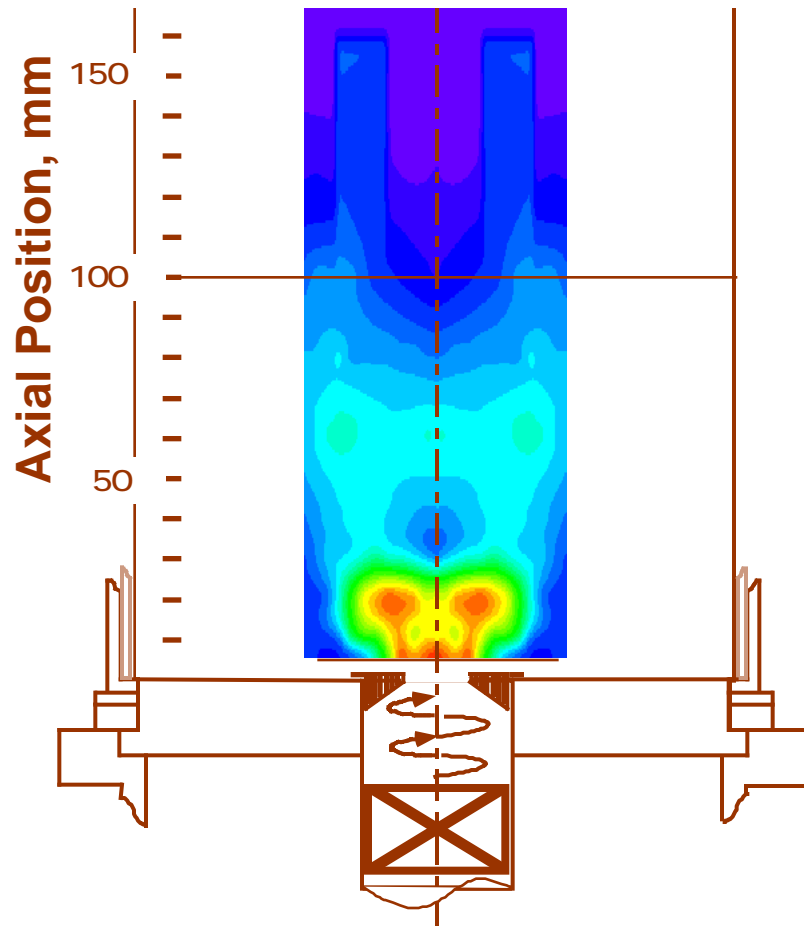


(F) - Mole Fraction H₂O (Mass Balance)

Iso-Concentration Contours of Unreacted H and C with the ATS-MS Burner

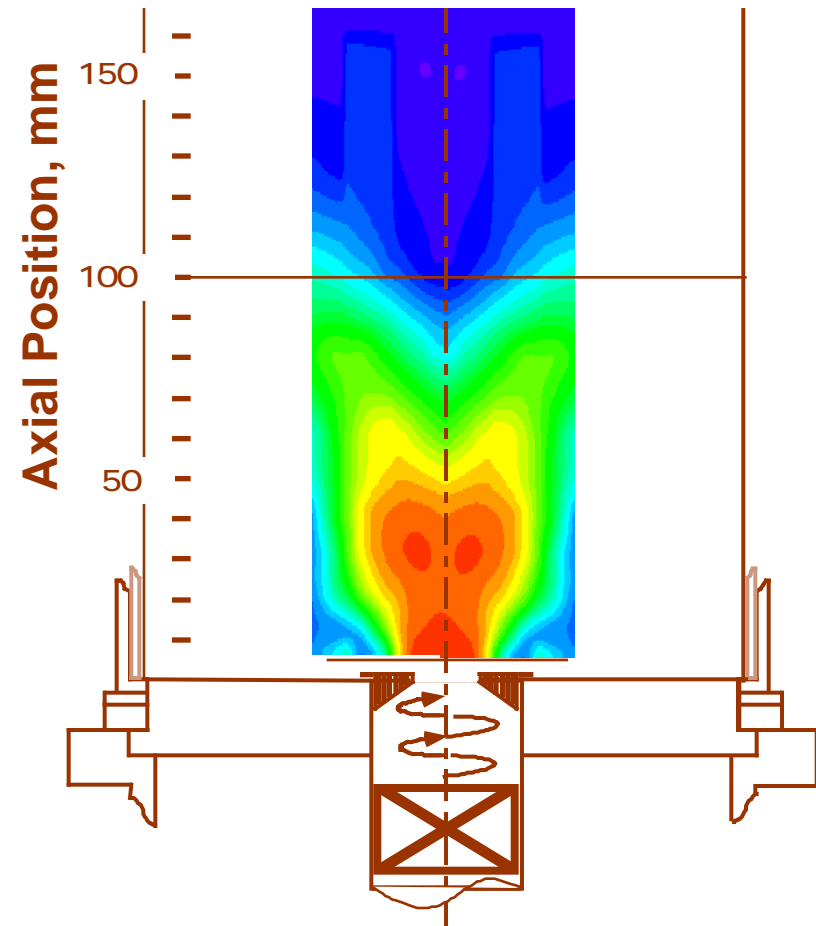
(Premixed Natural Gas/Air, Air Flow Rate = 500 slpm, $\phi = 0.65$)

Unreacted H



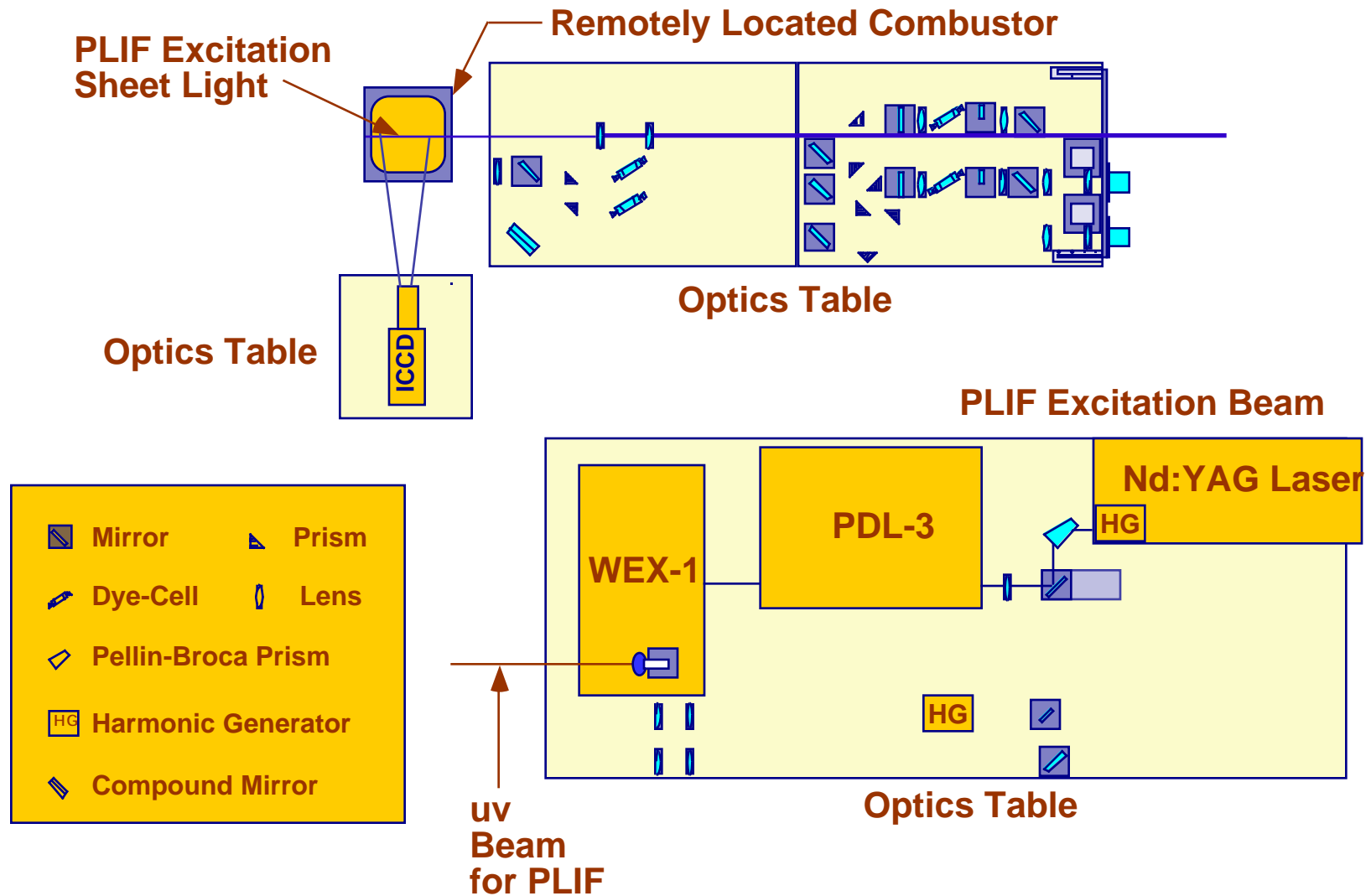
0.00 0.02 0.04 0.06 0.08 0.10 0.12
(G) - Mole fraction Unreacted H (Mass Balance)

Unreacted C



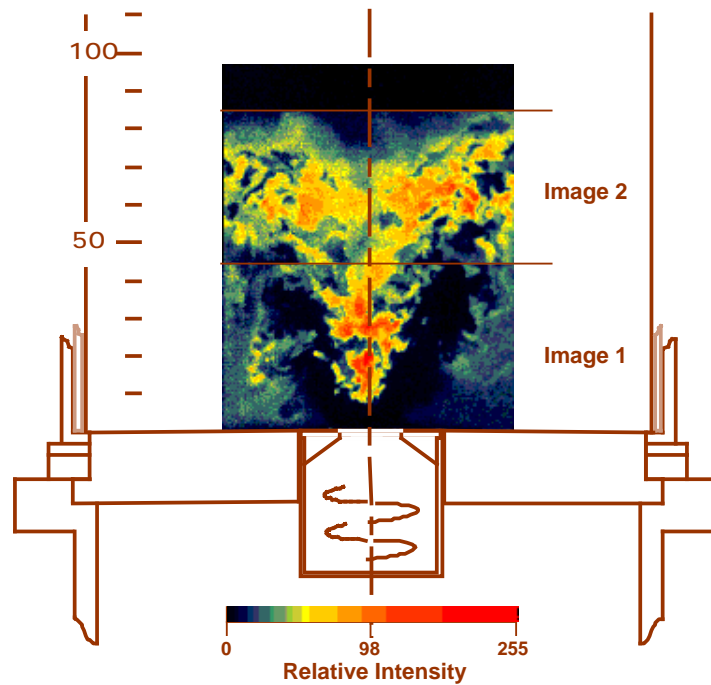
0.00 0.01 0.02 0.03 0.04 0.05 0.06
(H) - Mole Fraction Unreacted C (Mass Balance)

Schematic of PLIF Installation on the LSGTC



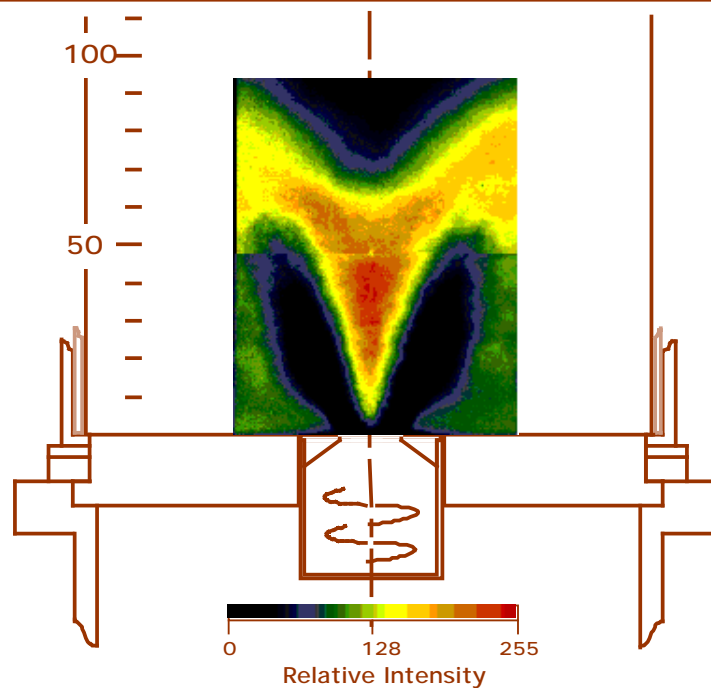
Example Instantaneous PLIF Images of OH Radical

(ATS-MS Burner, Premixed Natural Gas/Air, Air Flow Rate = 500 slpm, $\phi = 0.80$)



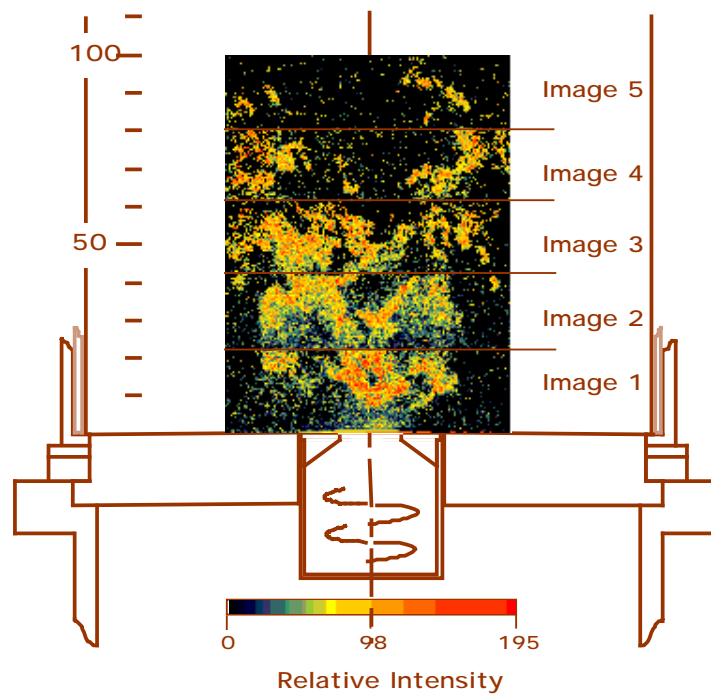
Mean of 128 Instantaneous PLIF Images of OH Radical

(ATS-MS Burner, Premixed Natural Gas/Air, Air Flow Rate = 500 slpm, $\phi = 0.80$)



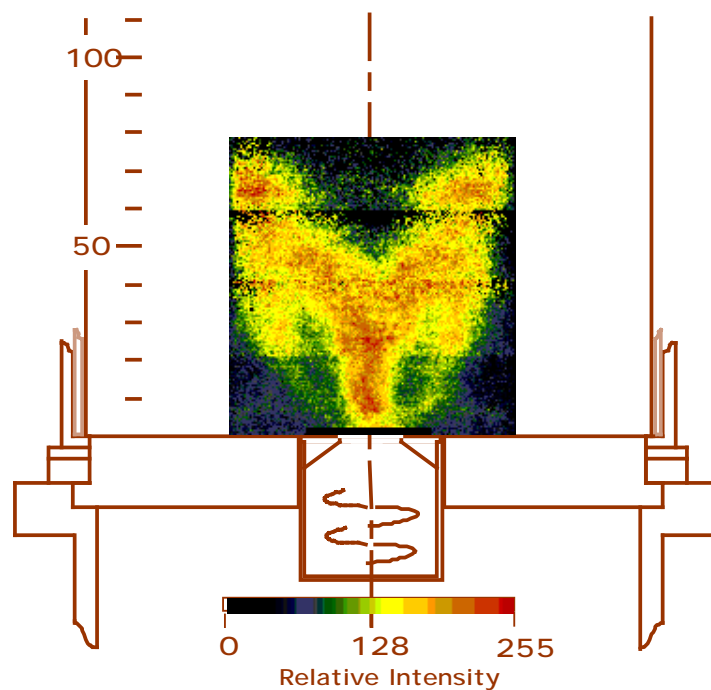
Example Instantaneous PLIF Images of CH Radical

(ATS-MS Burner, Premixed Natural Gas/Air, Air Flow Rate = 500 slpm, $\phi = 0.80$)

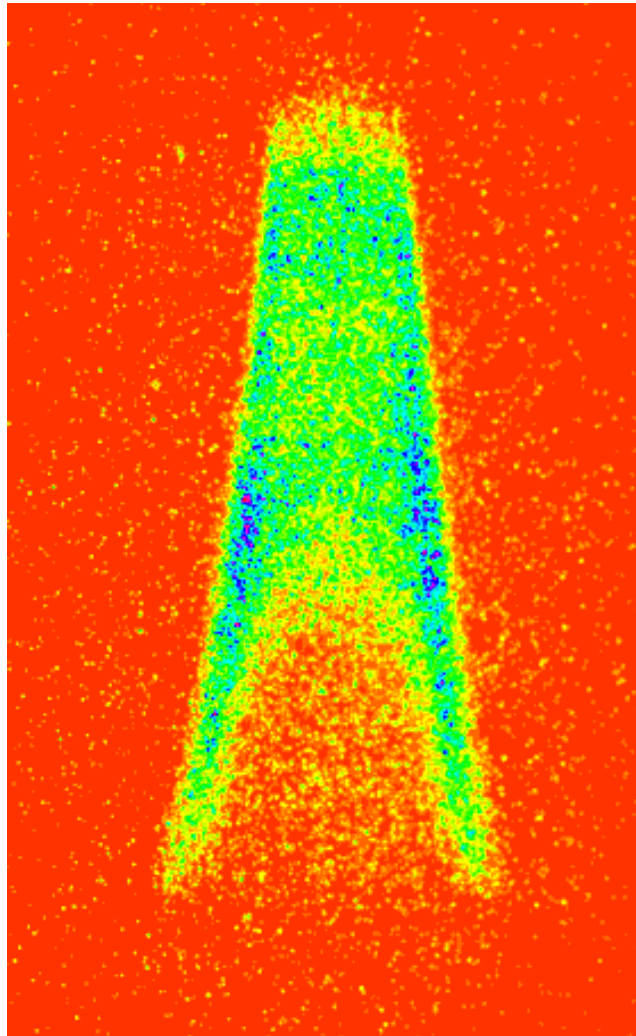


Mean of 64 Instantaneous PLIF Images of CH Radical

(ATS-MS Burner, Premixed Natural Gas/Air, Air Flow Rate = 500 slpm, $\phi = 0.80$)



**NO PLIF Image in a Laminar, Premixed Ethylene/Air Flame
(ca 225.6 nm Pump Laser; ca 234-237 nm Fluorescence)**



Conclusions/Results

- **New model for lean premixed systems**
- **New reduced mechanisms for lean premixed combustion**
- **Temperature, species, and PLIF image data obtained in laboratory-scale gas turbine combustor**
- **Reasonable comparisons with data from laboratory combustors**
- **First ever predictions of NO in premixed methane flame with PDF method**
- **First practical 3-D combustion calculations with velocity-scalar PDF method**
- **Code user's manual written**
- **Code available for beta testing**

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- **Prof. J.-Y. Chen, U. Berkeley, for advice and collaboration on reduced chemical mechanism**
- **Prof. Stephen Pope, Cornell U., for advice on PDF method and algorithm for in-situ table generation**
- **BEAM Tech., Inc., Dr. Gal Berkooz and Prof. Pope for use of PDF2DS, a 2-dimensional PDF program**
- **Prof. Robert Pitz and students at Vanderbilt U. for lean premixed flame data**
- **Dr. Mehran Sharifi, Westinghouse Elec. Corp., for premixer and combustor geometries**